Towards a Model of GaAs MESFETs for the Design of Cryogenic Integrated Circuits.

D. V. Camin, G. Pessina, E. Previtali
Dipartimento di Fisica dell'Universita' and INFN Sezione di Milano
Via G. Celoria 16, 20133 Milano

Margherita Pillan
Politecnico di Milano, Dipartimento di Elettronica e Informazione.
Piazza Leonardo da Vinci, 32. 20133 Milano, ITALY.

ABSTRACT

The read-out of cryogenic detectors for nuclear and particle physics, requires compatible front-end electronics operating at low temperature. GaAs MESFETs exhibit suitable DC and noise characteristics at the temperatures of interest (77 K and 4 K).

Since at cryogenic temperatures the electrical characteristics of the GaAs MESFETs differ significantly from those typical of 300K, a new model must be developed to employ computer circuit simulation during the design.

INTRODUCTION

The group of Milano has been working for many years in the design of low noise preamplifiers based on GaAs MESFETs, for applications with cryogenic particle detectors [1]. Bolometric detectors and liquid Argon (LAr) calorimeters have benefited from the results of this research.

Bolometric detectors are placed inside a dilution refrigerator at temperatures of the order of few mK. In order to prevent the integration of the signal in the parasitic capacitance of the link and to reduce external disturbances, it is necessary to place the preamplifier as close as possible to the detectors. The optimum condition has been reached placing the front end in the 4 K region. GaAs MESFETs have been selected as active devices as they are the only devices capable to operate with satisfactory noise performance at 4 K.

In order to optimize these devices for low temperature applications, we have designed and tested MESFETs with different geometries, using a commercial monolithic ion-implanted process. DC measurements have been performed at 300 K, 77 K and 4 K and the experimental data have been analyzed to study the dependence of the device parameters on the temperature.

Existing MESFET models, developed assuming room temperature operation, are no longer valid at cryogenic temperatures. We are interested in the development of a specific model to explain the physical mechanisms which determine the collected data: our very first results are presented in this paper.

GaAs low-noise preamplifiers have been designed and are used in the read out of a liquid argon (LAr) calorimeter, a detector for experiments in high energy physics. The speed requirement for this type of detector is tight. In fact the peaking time of the signal after shaping must be of the order of 20 nsec that is very short compared with those typical of standard particle detectors, and the electronics must be operated very close to the detector, therefore immersed in the LAr, at 87 K.

The device model we are working on will be of benefit in the design of MESFET's and analog integrated circuits optimized for the mentioned applications.

MESFET MODEL DESIGN

In most general purpose simulation programs, such as SPICE, the analysis of a non-linear circuit is reduced to the solution of a non-linear system of differential equation which is obtained applying the Modified Nodal Analysis. By using numerical integration techniques, the differential problem is reduced to the solution of an algebric non-linear system of equations, which is usually solved by a Newton iterative method.

In order to be implemented in a general purpose circuit simulator, a device model must be characterized by continuous equations describing the device current and charge behaviour, as a function of the unknown node voltages. The first derivative of these equations must be also analytically evaluated in order to reduce the computation burden associated to the model in the circuit simulation.

Furthermore, since during the Newton method iterations, the node voltage values can fluctuate significantly, the device model must present a numerically robust behaviour even for voltage values that are not of interest for physical applications.

Regarding its use for the design of integrated circuits, a device model should be accurate, flexible with respect to modifications in the fabrication technology , and simple.

The parameters characterizing the model, should have a physical meaning, or at least, they should have a significant effect on the device electrical characteristics, so that they can be easily extracted from experimental measurements.

The aim of this work is to design a MESFET model reproducing the electrical characteristics of GaAs depletion mode devices operating between 4.2 K and 120 K.

Since RF measurements at these temperatures are very critical, and commercial test equipment for high frequency characterization may be difficult to operate with standard cryogenic refrigerators, for the time being we point to a model mainly valid for DC, even if the application circuits are DC coupled dominant-pole amplifiers with transition frequencies up to 1GHz.

The devices we intend to model, are fabricated using a recessed technology on ion implanted material. They have gate lengths typically between 2 and 3 μm, selected for best noise performance.

MESFETS AT CRYOGENIC TEMPERATURES

Several effects influence the operation of a device at cryogenic temperatures [2].

The low-field mobility of electrons in a typical MESFET channel increases upon cooling down, due to the reduction of phonon scattering. A maximum value is reached at about 100 K and further cooling makes mobility drop again. Saturation velocity increases also upon cooling. At 77 K it is 1.5 to 2 times larger than at room temperature. The lower effective mass of the electrons in GaAs determines two effects: the ionization energy for the dopant impurities is low (6 meV) and the semiconductor becomes degenerate at a relatively low dopant concentration. At normal doping concentration there is possibly no freeze-out of carriers even at the lowest temperature.

To illustrate some low temperature effects, we show in Fig 1, 2 and 3 the I-V curves obtained in our laboratory of some test devices .

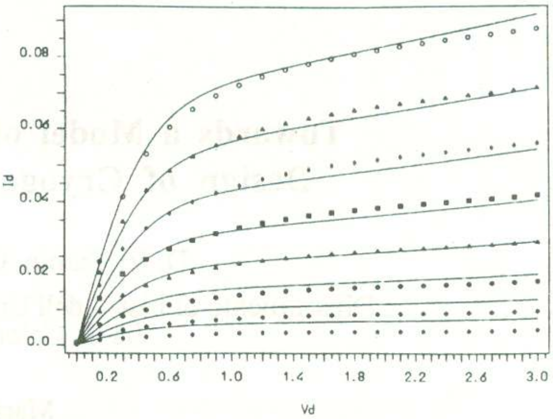

Fig. 1 - I-V curves for measured (point) and simulated (continuos line) for a MESFET at 300K.

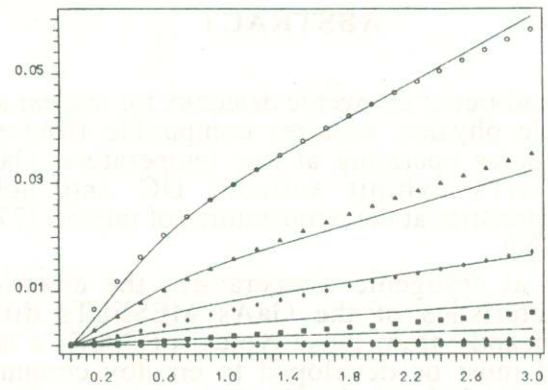

Fig. 2 - I-V curves for measured (point) and simulated (continuos line) for a MESFET at 77K.

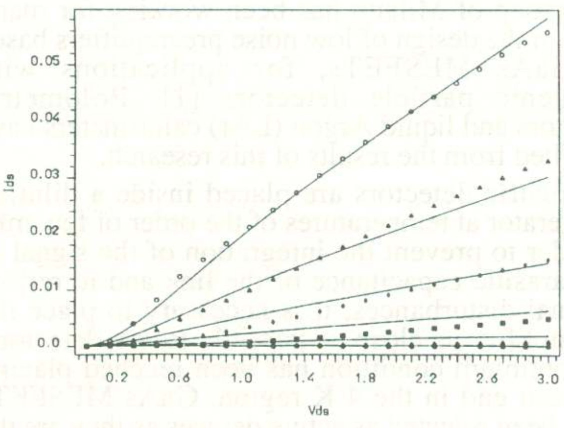

Fig. 3 - I-V curves for measured (point) and simulated (continuos line) for a MESFET at 4K.

Threshold voltage increases and current decreases when cooling to very low temperatures. A reduction of 100K originates an increase of about 0.2 V. The origin of this shift is attributed to the increasing of the substrate-channel built-in voltage, corresponding to the buried space charge region. In an analog way, the low temperature produces an increasing in the Schottky junction built-in value, and these two effects contribute to reduce the effective channel section.

For MESFET with gate-length shorter than 3 μm, the channel free carrier concentration at low temperature, can be significantly modified by mechanical stress effects, due to the presence of a passivation layer, over the active device. In a recent paper, Wong et al. [3] presented data demonstrating that the capping layer and the Schottky barrier built-in voltage variation, are responsible for about 90% of the measured threshold shift, in short gate devices.

It can be seen from the comparison between the here reported I-V characteristics at different temperatures, that the decrease of the temperature, produces a reduction of the curve steepness in the linear region and a degradation of the output resistance in the saturation area.

The increase of the channel resistance in the linear region of the I-V characteristics, is mainly due to the reduction of the undepleted channel section, corresponding to the low temperature widening of the two space charge regions. Furthermore, since the measured devices have a gate length of 4 μm, we can suppose that at low temperatures, the mechanical stress due to the passivation layer, does not produces a significant reduction of the free carrier concentration in the channel.

The low temperature behaviour of the output resistance can be mainly related to a backgating effect due to the widening of the space charge region at the active channel-substrate interface. At high fields, the electron flowing in the channel are not strictly confined in the undepleted section, and they flow in the buried space charge region, so degradating the output resistance.

Another effect that may constitute a severe limitation in the operation of GaAs MESFETs in cryogenic environments is the *collapse* phenomenon [4]: some devices present a change in their static characteristics after being subject to a large drain-source voltage excursion at cryogenic temperatures. This effect is attributed to the trapping of hot carriers in the interface between gate and drain and sets a limit on the maximum voltage excursion that a MESFET should sustain at cryogenic temperatures.

SOME EXPERIMENTAL RESULTS

We have measured DC characteristics at low temperatures of several devices using a modular system HP 4142 controlled by an HP9000 workstation. Devices are directly immersed in the LN or LHe.

The low temperature measurements are very critical for several reasons. Low temperatures characterization require long cables interconnecting the device under test to the instrumentation, and that can produce oscillation of the device or the presence of parasitic effect in the data collected. In order to avoid the oscillations the devices must be mounted in expecially designed jig. Furthermore collapse effects at 4K must be avoided by careful controlling the bias of the devices.

In figures 1, 2 and 3 we also report the simulation results obtained using the Statz model [5] to reproduce the I-V MESFET characteristics. It can be seen that for low temperatures the model does not fit the experimental data with sufficient accuracy. For low noise applications we need a model with maximum accuracy in the low-field region of the I-V characteristics.

In the Statz model the drain-source current is expressed by the equation:

$$I_{ds} = \frac{\beta(V_{gs} - V_{th})^2}{1 + b\,(V_{gs} - V_{th})}$$

As it can be observed from the experimental data, at low temperature the threshold voltage depends on the drain-source voltage and the Ids vs Vgs characteristics have no quadratic dependence any more.

In order to extend the Statz model to 77K applications, we substituted the previous equation with the following:

$$I_{ds} = \frac{\beta(V_{gs} - V_{th}(V_{ds},T))^{\tau}}{1 + b\,(V_{gs} - V_{th}(V_{ds},T))}$$

where τ is a function of the temperature.

In the 4K range (fig. 3) the I-V curves exhibit a change of curvature which can be due to the presence of the collapse phenomena and to backgating effects, which become relevant at this temperature.

Up to now we model the MESFETs behaviour at 4K using a non linear voltage controlled resistor.

CONCLUSIONS

No general model describing the behaviour of a MESFET from room to cryogenic temperatures have, up to now, been established. We have started a systematic study of devices manufactured in an ion-implanted process to arrive to a model to be simulated with time domain circuit simulators like SPICE.

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